Integration of Life Cycle Assessment Tools in the Design Process of Low-Carbon Buildings

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Sahar Mirzaie, BSc, MEng, LEED AP, PhD Candidate at Centre of Excellence in Sustainable Building Design, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, UK, sm76@hw.ac.uk (Principal Author)

Gillian F. Menzies, BEng, PhD, CEng, CEnv, Associate Professor, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, UK

Abstract

Given that more than 50% of the total UK carbon emissions are attributed to buildings, prognosticating, comprehensive, actively applicable tools are required to promptly commission a step-change in building design and construction performance. Integration of Life Cycle Assessment (LCA) tools such as BREEAM and BIM assists in designing and developing low-energy, sustainable buildings by providing a holistic perspective and approach. This study performs a critical review of the energy and carbon LCA research in the building sector in the UK since 2000. It proceeds with a comparative evaluation of three current Embodied Carbon LCA tools: Two BRE tools and SimaPro Software, and discusses the importance of the futuristic modes of LCA using BIM. Further, this research establishes the influence of used tools on embodied carbon performance of main building elements of a case study building that is procured and is under construction on Heriot-Watt University Campus using BREEAM and BIM.

Keywords: LCA, Embodied Carbon, BREEAM, BRE Green Guide, SimaPro, BIM

1.0 Introduction

The building construction sector in the UK releases over 29Mt of carbon dioxide annually (1). The built environment was accountable for over 190Mt of carbon dioxide in 2010, 17-20% of which can be categorized as embodied carbon (2). The projected emissions scenarios by 2050 raises the urgency of step-change solutions for meeting the 80% carbon reduction targets. On the same year the Department for Business, Innovation and Skills estimated that construction can influence up to 47% of the total CO_2 emissions in the UK and within the construction process, materials and components manufacturing is accountable for the largest sum of emissions (3).

Various Life Cycle Assessment (LCA) tools have been developed to evaluate and to recognize the environmental impact of construction projects. Given the size of the challenges involved in a building LCA, the outcomes are databases, tools, and studies with different calculation accuracy and semi-transparent results, which are inherently incomparable. Yet as the LCA study is increasingly used in construction practise, accurate, prompt, and cost-effective prediction of embodied energy and carbon increasingly gain significance and financial value. Thus, it is vital to evaluate the current assets against each other to be able to benefit from the appropriate tool depending on the right intent and project stage and to develop a far-reaching solution.

This paper will contribute to the direction of such efforts in the UK construction industry through comparing a selection of the most commercially popular (BRE tools (4) and SimaPro (5)) and futuristic (BIM) modes of LCA and the key literature on the topic. The results contribute to understanding the various stages of LCA, important building materials and components and their share in the total carbon emissions, as well as the influence of the quantifying tool in the final results through comparison of case study results against reflected literature.

The paper is organized as follows. Section 2 reviews the LCA literature in the UK since 2000. Section 3 provides a detailed overview of the considered LCA tools, followed by section 4, which introduces the case study and its findings. The results are discussed in section 5 and the paper concludes in section 6.

2.0 Building LCA research in the UK: A 15 year critical review

Although literature specific to the LCA of building construction in the UK is scarce, in this section, methodologies, scopes, tools, and results employed among several of the key studies during the last 15 years, as charted in Table 1, are discussed. LCA of building construction can be performed to assist decision-making at different levels:

- Level 1. a) Construction products and materials such as concrete, steel, or tiles; b) Major building elements (components) such as walls or upper-floors;
- Level 2. Whole building, which apart from Level 1 elements also includes the electro-mechanical systems and sub-structural elements.

Consequently, some studies are restricted to main building materials and components while others have evaluated whole buildings. Despite the inconsistent boundaries and methodologies used, their results can be compared and interpreted with careful attention specifically to the LCA scope. In addition, in order to assess the impact of an LCA study on an actual building's embodied emission, it is imperative to take note of the project stage when LCA was introduced in the project, how were the data collected, and which team members have undertaken the study (6).

Figure 1 illustrates the various stages of a building construction lifespan and the alternative LCA boundaries. The word "Embodied Impacts" represents a broad notion that can include Initial, Recurring, and End-of-life stages. Further breakdown of this term is into six groups as illustrated in Figures 1 and 2: 1) Cradle-to-Gate embodied carbon of building materials; 2) Carbon emissions due to transportation of materials and workforce to the project site; 3) Carbon emissions due to site activities and building construction; 4) Recurring carbon emissions due to project refurbishment and maintenance; 5) Carbon emissions due to site activities for building deconstruction and transportation of waste and workforce; 6) Carbon emissions of waste materials treatment.

This ambiguity in definition is one of the reasons behind the discrepancies and divergence in results of various studies. Figure 1 shall be read in conjunction with figure 2, which presents the total embodied carbon emissions of the literature reviewed in this section (except the first two) and their scope of study. It is important to note that the shown embodied carbon emissions are normalised to gross internal floor area (GIFA), also known as habitable floor area, as the Functional Unit for the purpose of comparison.

One of the first building LCAs of the current millennium in the UK was by *Yohanis et al.* (7), which studied the embodied and operational energy of the substructure, envelope, finishes, and heating system (Level 2) of a generic open-plan office. They compared the embodied energy of materials versus operational energy of the office over different building life-time periods. Embodied energy of the single storey office of *Yohanis et. al.* was reported 9.5 [GJ/sqm] from Cradle-to-Grave.

Asif et al. (8) performed an LCA of the extraction and processing of the most significant construction materials (Level 1.a) in a duplex house based on generic data, respectively being: concrete, ceramic tiles, timber, glass, and aluminium. Concrete is responsible for

65% of the embodied energy and more than 99% of the CO_2 emissions accounted. The amount of concrete used disregards its lower embodied energy and carbon emission when compared to aluminium, glass, or ceramic tiles. The embodied energy of the *Yohanis* office was reported much higher than the Asif house (9.5 and 2.1 [GJ/sqm], respectively), because *Asif et al.* only studied a portion of embodied energy from Cradle-to-Gate of eight materials with the most significant impact (similar to Hammond's work in 2008), while *Yohanis et al.* estimated the embodied energy from Cradle-to-Grave of the whole building.

Given the high embodied energy of heavy weight materials, *Hacker et al.* (9) decided to explore the effect of thermal mass of different material compositions from a broader perspective. Thus, they studied the embodied and operational CO_2 emissions of four different compositions from lightweight Timber and Brick to heavyweight concrete buildings under present and anticipated climate circumstances. Their conclusion was that although heavier weight cases have higher embodied carbon (Figure 2), they result in up to 17% lower emissions over their lifetime due to the reduced operational emissions.

According to Yohanis' study in 2002 (7), embodied emissions of building construction is equivalent to 15-18 years of operational emissions, while Hacker's study in 2008 (9) concluded that these numbers rise to 21-25 years of operational emissions. This signifies the importance of accurate embodied energy and carbon as the industry succeeds in reducing the operational energy of buildings.

The influence of various building use types on carbon emissions is the main theme of *Sansom* and *Rojer* investigation (10). The results of their study have shown that the share of structure materials (frame and upper-floors) in the total embodied carbon emissions has increased from 14-22% to 48-68% in low-rise to high-rise buildings. This is while in low-rise buildings foundation, ground, and external works dominate the total embodied carbon emissions. The reason could be attributed to the sturdier structure required to support the additional load of vertical transportation and HVAC equipment. This effect has been in rise since the bloom of all glazed curtainwall towers due to their higher need of and reliance on active air-conditioning (11). Similar results were reported by *Sharma et al.* (12) in the American construction sector.

One of the most comprehensive studies to date is a Cradle-to-Cradle LCA of a skyscraper in central London (13,14), which includes the emissions of material delivery to the site, on-site activities, maintenance, and end-of-life stage. As Figure 2 depicts, the embodied emissions of this tower is almost double that of other studies (1018 [$kgCO_2$/sqm]), where raw materials represent 51% of the total embodied emissions (519 [$kgCO_2$/sqm]). This clarifies the impact of increased occupancy per building footprint on the total embodied emissions, and presents the idea of considering occupancy as the Functional Unit for comparison purposes. The contribution of other processes in the total embodied emission of this high-rise is as follow: 2) delivery of materials to construction site 6%, 3) onsite activities 3%, 4) maintenance 39%, and 5-6) end-of-life 1%.

72% of dwellings in the UK are built following 3 typical layouts. *Cuéllar-Franca and Azapagic* (15) studied the Cradle-to-Cradle embodied and operational Global Warming Potential (GWP in tonnes CO_2 eq.) of these forms, namely: detached, semi-detached, and terraced. When looking to the spread of GWP over the lifetime of these buildings, the main consumption is during use phase, representing 70 to 90% of the total emissions, followed by embodied GWP with 9% share.

One of the reasons that there were so few building LCA studies up until 2008 is that LCA researchers were struggling to populate inventories due to a lack of comprehensive databases. In order to address this shortcoming and provide a better basis for comparison of LCA studies, *Hammond and Jones* developed an open-access database of embodied energy and carbon emissions coefficient based on Cradle-to-Gate LCA study for 200 different materials in the UK, termed the *Inventory of Carbon and Energy (ICE)* (16).

In an effort to demonstrate the ICE's application, they used it for LCA of fourteen new dwellings across the UK. They observed that the difference in impacts of apartments and houses is not significant, unless the non-habitable and external areas are included. The authors attributed 19% of the total embodied carbon in a typical UK dwelling to waste and suggested responsible management of materials during design and construction as one of the most advantageous methods of impact reduction (1). Battle (13,14) suggested additional emission reduction strategies by estimating the impact of reclaimed steel structure and locally sourced materials to be -3.3% and -6%.

On the same topic, *Monahan et al.* (17) studied the effect of modern construction methods on the embodied energy and carbon emissions of a typical house. This study concluded that the off-site modular insulated timber frame house has 34% less embodied carbon when compared to the conventional modes of on-site construction. It is interesting to note that even though timber is the principal material used, concrete with 36% share, still has the highest contribution to the total embodied CO_2.

The reviewed literature have mostly considered major building construction materials and have excluded mechanical, electrical, and interior elements. Moreover, only very few literature have studied the whole building life-span and mostly have considered the initial embodied impacts only. Battle reported significantly higher embodied carbon for the 21 storey high-rise studied from Cradle-to-Cradle (13,14). Looking at the results reported for the first category of embodied carbon in figure 2, which is about 50% of total embodied emissions, it seems that the reported results are in good agreement with other studies. Since this is the only study considering the full lifespan (over 60 years) of an actual project, it is a good indication of amount of embodied carbon that is dropping out of other calculations.

Using average share of each embodied impact category, as illustrated in Figure 1 and 2, can be calculated based on a representative number of projects. This can help conjecture embodied carbon of different studies' missing scope. From these small number of studies it seems that the share of embodied carbon categories is as follows: 1) 30-50%, 2) 2-5%, 3) 2-5%, 4) 20-30%, 5)1-3%, and 6) 1-3%.

Table 1: Details of publications on building energy & carbon LCA in the UK since 2000

Reference	Cases studied	Scope of LCA study	Tool, Resources, Inventory, Method	Environmental Impacts Studied
Sansom et al. 2012 (10)	Five commercial buildings: Distribution warehouse, Supermarket, Secondary School, High-rise Office, & Mixed-use	Level 1, Materials & components excluding building services, internal finishes, fit-out (Three different structural compositions)	Actual project data, Literature, ICE, CLEAR GaBi (ISO 14040/44), IES software suite	Embodied and operational carbon Costs
Cuéllar-Franca *et al. 2012* (15)	The three main types of UK housing (detached, semi-detached and terraced) over 50 years	Level 1, Materials & components excluding building services, internal fit-out and finishes	Literature, ISO 14040/44, Ecoinvent, GaBi V4.3, CML 2001	Embodied and operational energy, GWP (kgCO2 eq), acidification, eco-toxicity, etc
Monahan *et al. 2011* (17)	A three-bedroom semi-detached duplex house in Norfolk	Level 1.b, Major building elements for two modern off-site modular timber frame construction versus on-site construction	Actual project data, Literature, ICE, Ecoinvent, U.S. Life-Cycle Inventory, Simapro V7.1, ISO 14040/44	Embodied energy and carbon dioxide emissions
Battle 2010 (13,14)	Ropemaker Place, a 21 storey office building with 3 basement levels over 60 years	Level 2, Foundation to Cat B Fit-out Different material compositions and other energy saving scenarios	Actual project data, Literature, ISO 14040/44, dcarbon8	Embodied and operational carbon Costs
Hammond *et al. 2008* (1)	14 houses and apartments: 2 in the US and 12 in the UK	Level 1.a, Major building materials	LCEA Literature, actual project data, ICE, ISO 14040/44,	Embodied energy and carbon dioxide emissions
Hacker *et al. 2008* (9)	A two bedroom semi-detached duplex house in south-east England over 100 years	Level 1.b, Major building elements for four different material compositions with various thermal mass	LCEA Literature incl. IStructE & BRE Environmental profile database, ISO 14040/44, Energy Modelling (ENERGY 2)	Embodied and operational carbon dioxide emissions
Asif *et al. 2007* (8)	A three-bedroom semi-detached duplex house in Scotland	Level 1.a, Eight significant materials in the building construction	LCEA Literature, ISO 14040/44	Embodied Energy, Global Warming Potential (CO2, SOx, NOx)
Yohanis *et al. 2002* (7)	A generic single-storey open-plan office building over 25,50, and 100 years	Level 2, Full building: substructure, envelope, windows, finishes, and heating	LCEA Literature, Early Design Model (EDM)	Embodied and Operational Energy

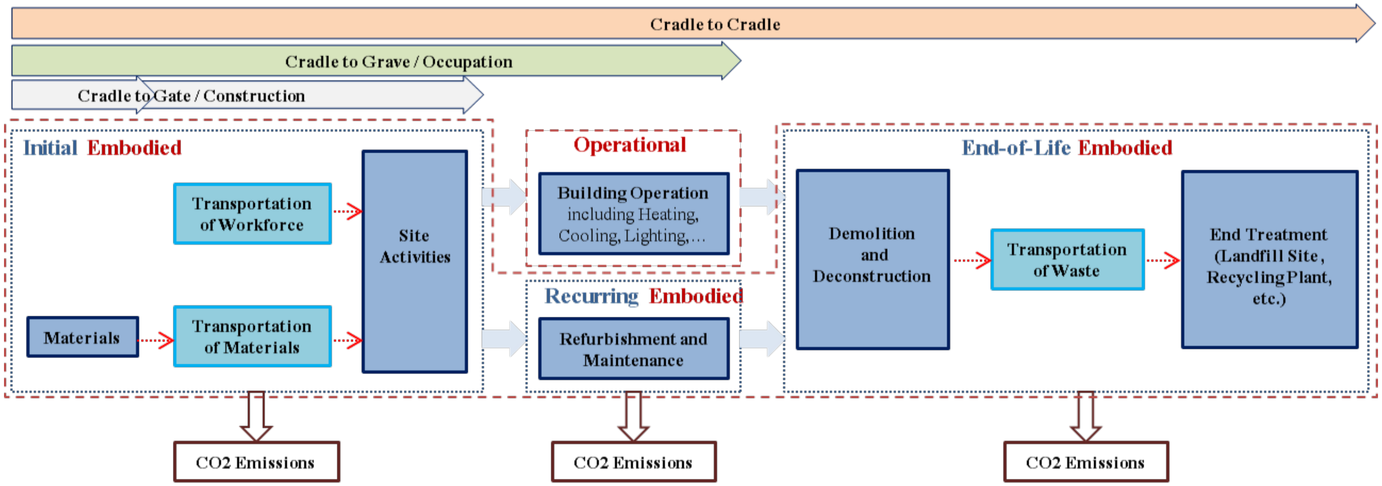
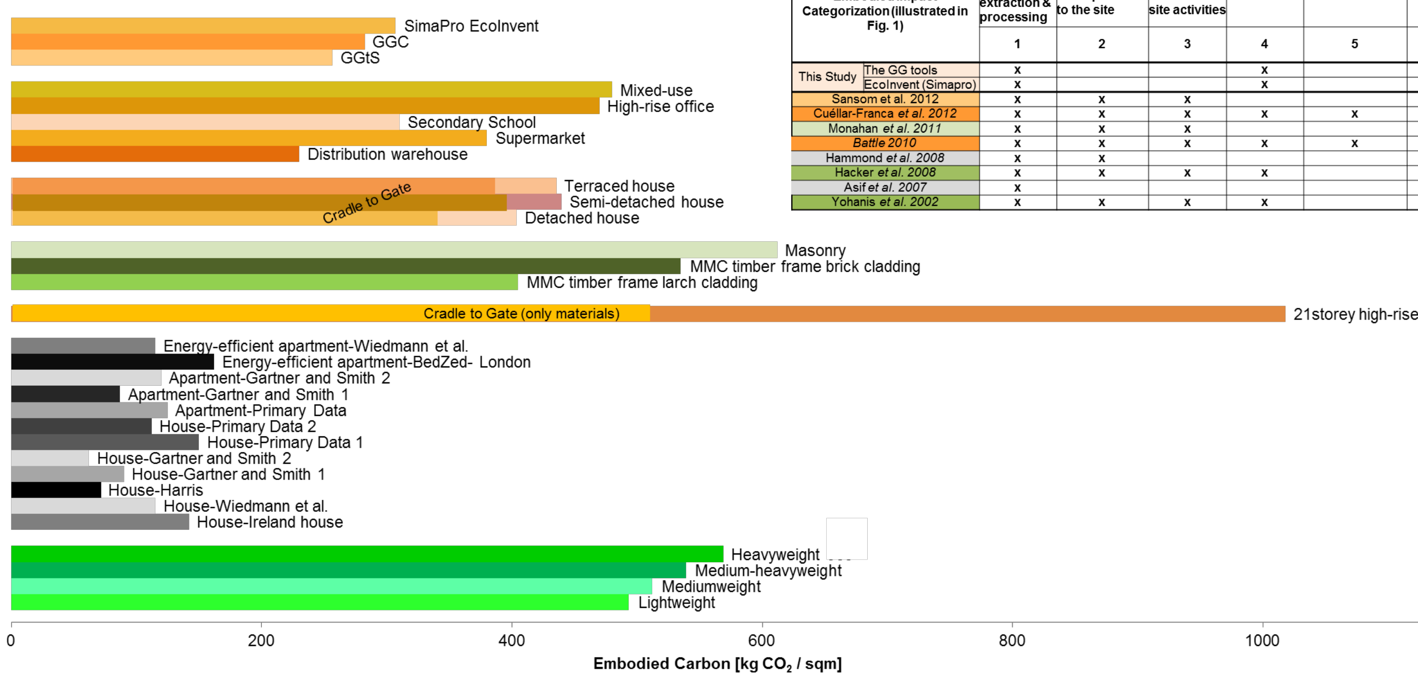


Figure 1: System boundaries and flow diagram for whole building LCA

Reference	LCA Scope: Cradle to-
This study	Cradle (Except transportation and site activities)
Sansom et al. 2012	Cradle (Except maintenance & deconstruction)
Cuéllar-Franca et al. 2012	Cradle
Monahan et al. 2011	Occupation / Grave
Battle 2010	Cradle
Hammond et al. 2008	Construction (Excludes site activities) / Gate
Hacker et al. 2008	Occupation / Grave
Asif et al. 2007	Construction / Gate
Yohanis et al. 2002	Occupation / Grave



Embodied Impact Categorization (illustrated in Fig. 1)		Cradle to Cradle / Cradle to Grave / Occupation / Cradle to Gate / Construction Site: Material extraction & processing	Transportation to the site	Construction site activities	Recurring	Deconstruction site activities	Waste transfer and end-of-life treatment
		1	2	3	4	5	6
This Study	The GG tools	x			x		x
This Study	EcoInvent (Simapro)	x			x		x
Sansom et al. 2012		x	x	x			x
Cuéllar-Franca *et al. 2012*		x	x	x	x	x	x
Monahan *et al. 2011*		x	x	x			
Battle 2010		x	x	x	x	x	x
Hammond *et al. 2008*		x	x				
Hacker *et al. 2008*		x	x	x	x		
Asif *et al. 2007*		x					
Yohanis *et al. 2002*		x	x	x	x		

Figure 2: Embodied Carbon scopes and results of LCA studied in the UK since 2000

3.0 Building LCA Tools in the UK

Similar to LCA studies, LCA Tools can also be regarded as working at two levels based on the extent of their application:

Level 1. Product and building component comparison tools such as BRE Green Guide to Specification (GGtS) and Green Guide Calculator (GGC) (4,18).

Level 2. Whole building design decision support tools such as IMPACT (formerly known as Envest) (19).

BREEAM (Building Research Establishment Environmental Assessment Method) is the most-widely used tool in the UK to assess the environmental performance of a building during design and construction (20). BREEAM is a credit-based method, where team parties cooperate to abide by the requirements of certain targeted credits to achieve a desired rating of Certified, Good, Very Good, Excellent, or Outstanding. Among the BREEAM credits, "Material 01: Life Cycle Impacts" looks at the life cycle impacts of the main building elements, using CO_2 as the reference substance, based on 60-years lifetime. Through allocating two points for undertaking a Level 2 LCA, the BRE encourages whole building study, yet offers an alternative route of assessing the major building elements using the Green Guide tools as a Level 1 assessment for 1 point.

The BRE GGtS (4,21) was first introduced in 1996 and ever since has been developed to what is currently extensively used in the industry by almost all projects targeting BREEAM certification. In order to determine the relevant embodied carbon and GG rating, the BRE assessor chooses the specification with the closest description to the design proposal. However, given that the GGtS database only includes about 1500 building element specifications, in some cases a component with the desired material make-up is not available. In such situations, the unknown environmental performance and rating of material compositions must be enquired and obtained from the BRE through a technical query sent by the BRE assessor. In 2009, in order to address this issue and reduce the number of technical queries received, the BRE developed the complementary GGC, where BREEAM assessors can build up the proposed design using the BRE material database.

As shown in the table of Figure 2, scope of the BRE GG database is limited to 1) manufacturing and installation, 3) refurbishment and maintenance, and 6) final disposal. Thus all material and waste transportation and site activities for construction and deconstruction relevant to the 2^{nd}, 3^{rd}, and 5^{th} categories are excluded.

Under the BREEAM issue: "Management credit 03: Construction Site Impacts", one point could be pursued for recording the transport of materials used in major building elements (as described in section 4) as well as ground-works and landscaping materials to and waste from the construction site. An additional point is awarded for monitoring and recording the energy use on site (22). Given that the BRE GG tools used for Material 01 credit assessment are missing transportation and site activities, these construction data can be integrated to the results of projects material LCA analysis. Through this incorporation and development of a more inclusive GGC, the construction industry can benefit from a significantly better LCA analysis and embodied impact estimation.

SimaPro software package, developed by PRé Consultants, is among the most-widely used LCA tools especially for products due to its modelling flexibility and broad Ecoinvent database (5,23). Simapro is a flexible, powerful LCA tool, which facilitates modelling the whole building with great level of details at both the levels described above. Thus, the current model, which is based on generic Ecoinvent database (23) can be expanded, customized, and adapted according to the actual project information including all the full building life-span and other materials. This will allow for a comparison with the current results to understand the portion of embodied energy that is commonly measured via the BRE tools in the mainstream industry. Additionally, it will clarify the role of operational embodied carbon emissions in this equation.

Although the BRE GG tools are increasingly used in the conventional practice and are powerful in familiarizing designers with the environmental consequences of their choices, the GG database is generic, limited, and rather static. Besides, the process of obtaining an unknown environmental rating of a new specification from the BRE can be a long wait, meaning that the team may proceed with the design resorting to the specification with the closest description to the proposed component design. Thus, there are circumstances where different assessments of a composition appear to have different embodied impact. According to the "The Society of Environmental, Toxicology and Chemistry (SETAC), 1993", LCA is an "objective" method to assess the associated environmental impacts of a product, process or activity (24). Using any generic tool and secondary data initiates the prejudice and human-error in final results.

Chamindika et al. (25) emphasized the main issues hindering using stand-alone embodied carbon analysis tools to be with databases' expansion and update, execution of design variations, and retrieving the current data and incorporating to the model. Building Information Modelling (BIM) is a 3D visualization model, which could overcome these issues and facilitate swift, precise cost and building performance estimations of any design alteration. Moreover, BIM facilitates better communication and transfer of data for instance design and construction knowledge to the facility managers after handover. Such a comprehensive tool is essential to broaden the scope of building assessments to accommodate a full LCA and integrate this exercise to the design process rather than pursuing it as an isolated practise for satisfying the requirement of building environmental assessment certification requirement (26).

A very recent study in 2015 in Australia concludes that tendency of project clients in performing a comprehensive cost-benefit analysis is among the many factors influencing low-carbon construction (27). In this study, 30 industry professionals were interviewed to investigate whether they base their design decisions on energy efficiency rating and carbon accounting. While energy efficiency seems to be a well understood and perceived concept, a common misunderstanding appears to exist regarding the relationship between carbon accounting and the industry performance. The potential of BIM in incorporating this analysis into the design process is an assurance to rectify the common misconception and to include environmental performance among the design factors.

4.0 Case study: Sir Charles Lyell Centre

The Sir Charles Lyell Centre, which is designed using BIM and BREEAM tools, is currently in the last stages of construction and is due for completion in February 2016 (Fig.3). Lyell will be the Centre for Earth and Marine Technology of Heriot-Watt University and is approximately 5,300m^2; designed for over 200 occupants. The project has achieved an Excellent rating at the Design and Procurement stage, reaching a score of 73.32% under the BREEAM 2011 New Construction for Education building type. According to the BRE, this rating level represents the top 10% of new UK non-domestic buildings (22).

The Lyell Centre targets 5 out of the 6 available points of the Material 01 BREEAM credit. These points are counted based on LCA assessment of material make-up of the major building elements using the BRE GGtS tool (4,21). The considered elements for Education building type include: external walls, internal walls, windows, roof, upper floor slab, and floor finishes and coverings. The scope of this paper focuses on these elements considered by the BRE and their emissions based on the 1st, 4th, and 6th embodied carbon categories described in previous section; hence, the building structure and foundation are excluded. Furthermore, in order to give recognition and encourage usage of materials with third-party verified Environmental Product Declaration (EPD), the contribution of such materials or products are amplified through a certain calculation procedure (as described in the BREEAM Manual (22)), which is out of this paper's goal line.

The selected building elements' specification was obtained through investigating the inventory reports at the design tender stage. The elements' embodied carbon is quantified using three tools: (1a) the BRE Green Guide to Specification (GGtS), (1b) the BRE Green Guide Calculator (GGC) (4,21), and (2) SimaPro 8 Software (5) and Ecoinvent 3 database (23). The result for each building element is displayed in Figure 4 and 5 and for the whole building is exhibited against the reviewed literature in Figure 2.

Using the BRE GGtS tool elements with closest description to Lyell Centre were chosen as per the evidence submitted for the project to the BRE towards project certification. It must be noted that the GGC tool does not include Windows and Floor Finishes.

Using IPCC GWP 100a impact assessment method, which is mainly used for Carbon Footprinting, the carbon emissions of building elements material composition were evaluated via SimaPro software package and Ecoinvent 3 database (5,23).

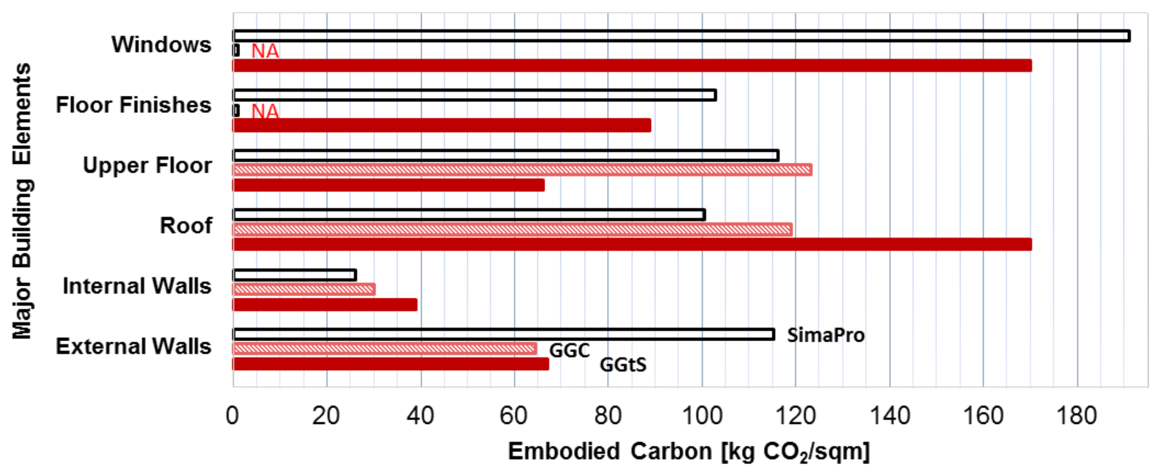


Figure 4: Embodied Carbon per square meter of the Lyell major building elements calculated with 3 tools

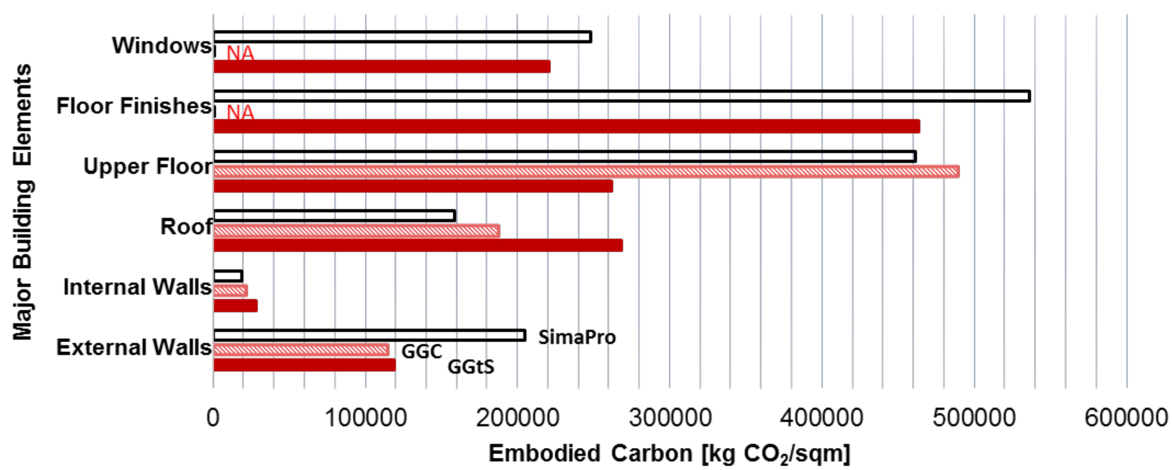


Figure 5: Embodied Carbon of the Lyell major building elements calculated with 3 tools

5.0 Discussion

In this study, Embodied Carbon of main building elements of the Lyell Centre as per the BRE recognition (described in section 4) were appraised using the two BRE GG tools (4,21) and SimaPro Software (5). For comparison purposes the results are visualised in Figure 4 and 5. Figure 4 represents embodied carbon per square meter of each major element. Sum of these emissions is also compared against the reviewed literature of section 2 in Figure 2, depicting that SimpaPro results in the highest prediction of the total emissions, while GGtS tool reports the lowest numbers.

As shown in Figure 4, Windows and Roof elements have the highest embodied carbon per square meter area, whereas Floor Finishes and Upper Floors show the highest embodied carbon due to covering larger areas (Figure 5). This is while Floor Finishes is excluded from many studies. The share of Internal Walls seems to be negligible, even though their emission per area is not considerably lower than the other building elements.

GGtS estimations for Upper Floors construction noticeably differs from the other tools, which could be attributed to inaccuracy of closest description in GGtS database to the actual design and the characteristics of structural precast concrete used. Similar scenario can be picked up for the Roof element. Another sizable discrepancy is for External Wall elements' calculations performed using SimaPro when compared to both the GG tools. This is primarily because Plywood Sheeting has positive embodied carbon impact in the BRE database. Moreover, steel framing is estimated to have relatively higher emissions based on the Simapro results.

The difference in results generated for the Lyell Centre using the three tools, pictured in Figures 4 and 5 for each building element and in Figures 2 in sum, is an example of the magnitude of possible error in embodied carbon calculation. For each building element the divergence is so significant that could mislead the perceived carbon efficiency. As shown in figure 5, the results of SimaPro and GGC are approximately 20% and 10% higher than the GGtS tool, respectively. Building LCA literature in the UK suggest that Cradle-to-Gate embodied carbon of building materials represent 30-50% of the total embodied carbon of a building. With the current estimations, the total embodied carbon of Lyell Centre can fall somewhere in 514-1024 [kg CO_2/sqm].

Further incentives should be provided to encourage use of more comprehensive tools such as SimaPro software. Additionally, the revisions in section 2 prove that a substantial portion of construction emissions are embodied in the envelope as well as the building structure. This is while the structure is currently not included within the BREEAM or GG tools scope due to a lack of representative functional unit. Currently, there is a significant room for improvement of GGC tool without introducing any additional calculation complications to address these shortcomings and assist designers in having better estimates of emission consequences of their decisions.

Environmental impact of buildings including Embodied Carbon emissions can be significantly reduced during the design stage through assessing alternative scenarios starting at early concept stage and throughout the process with the adoption of low impact solutions. Until the time that BIM is well developed technologically and is established among practitioners, alternative solutions are required to facilitate this transformation of the construction industry from traditional to automated practice. For instance, *Hamilton-MacLaren et al.* (28) has proposed a simple, flexible LCA calculation methodology to encourage analogy and adoption of the methodology as a design tool at early project stages at low cost, which can be adopted especially at projects concept stage when generic estimations are required as lack of actual specification delays thorough analysis.

6.0 Conclusions

In light of the magnitude of carbon emissions from the construction sector in the UK, this review compiles and reflects on highlights in building Embodied Carbon LCA over the last 15 years in the UK. As Table 1 reads, the LCA databases and tools, and accordingly the results of all these studies, vary along with different factors including data, scope, and user application. Thus, two of the key questions to ask when working with an embodied carbon LCA tool or analysing work of others is regarding the scope: 1) what life-cycle stages are considered and 2) what materials, components, and activities are included.

From this revision it appears that availability of comprehensive databases and tools during the last five years has greatly encouraged the tendency towards a Cradle-to-Cradle LCA and more inclusive studies. Although there are many challenges towards studying the full impact of a building, the aim is to ultimately establish a comparable measurement, and to create a foundation or a benchmark to build upon and to assess progress in moving towards more sustainable construction.

Despite all advancements in building automation and development of various LCA tools with different levels of sophistication, the choice of construction materials is still mainly influenced by building use type, design, aesthetic, and economic criteria. It is essential to find solutions to the current shortcomings of unconnected LCA tools. Effective integration of LCA tools into the design process is a challenge that could potentially be triumphed via comprehensive smart BIM tools. This will result in better decision-making, simplified and more accurate environmental rating assessment, and ultimately improved design, construction, and operation processes.

Furthermore, this study presents embodied carbon quantification of the main building elements of a case study building, currently under construction, using three different tools: GGtS, GGC, SimaPro. These are the most frequently used tools in the UK for decision making and abiding by the requirements of the BREEAM certification. The results clarify the degree of influence of assessment tools and suggest that under BREEAM LCA credits only half of building embodied impact is assessed. Future work is recommended to provide more accurate numbers to assist better conjectures about embodied carbon of different studies' missing scope and to elucidate building LCA procedures and its common pitfalls.

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